

CLAIMS

We claim:

1. A high resolution method for measuring seismic polar anisotropy in-situ in a region of
5 interest characterized by geological formation elements that reflect sonic energy, comprising the steps of:
 - (a) using a source to input sonic energy into the subsurface of the region of interest;
 - (b) recording sonic energy reflected from the subsurface of the region of interest by
using a plurality of sonic receivers that are located in a borehole that is located in the subsurface of the
region of interest; said borehole having an axis that is at a known acute angle relative to at least one of the
10 geological formation elements of said region; and
 - (c) interpreting said recorded sonic energy of said receivers in terms of both the
direct raypaths from said source to said receivers and the indirect reflected raypaths from said source to
said receivers to obtain a measure of the seismic polar anisotropy parameters V_0 , η , and δ .
- 15 2. The method of Claim 1, wherein steps (a) and (b) are performed using a sonic energy
source and a plurality of receivers that are located within said borehole.
3. The method of Claim 2, wherein said source and said receivers are carried by a sonde
that is adapted for axial movement within said borehole.
- 20 4. The method of Claim 3, wherein said axis of said borehole is at an acute angle relative to
the surface above said region; and wherein said geological formation elements comprise at least one of a
bedding horizon, a fault, and a layer boundary having a generally horizontal orientation relative to said
surface above said region.
- 25 5. The method of Claim 3, wherein said geological formation elements comprise at least one
of a dipping bedding horizon, a dipping fault, and a dipping layer boundary.
6. The method of Claim 4, wherein the indirect raypaths of step (c) include reflections from
30 geological formation elements comprising a plurality of lithologic horizons that are traversed by said
borehole at an angle that is greater than zero degrees and less than ninety degrees, and that is preferably
about 45 degrees; and wherein said axis of said borehole is deviated from the vertical.
7. The method of Claim 6, wherein step (c) comprises the step of measuring the anisotropic
35 phase slowness over a two-dimensional suite of directions, thereby characterizing the anisotropy of that
part of the subsurface traversed by said raypaths.

8. The method of Claim 7, wherein said anisotropic phase slowness is measured over a two-dimensional suite of directions by at least performing the following steps:

- (a) perturbing the positions of said receivers, and
- (b) measuring phase slowness along said axis of said borehole.

9. The method of Claim 7, wherein said anisotropic phase slowness is measured over a two-dimensional suite of directions by at least performing the following steps:

- (a) perturbing the position of said source, and
- (b) measuring phase slowness along the direction of an image of said borehole.

10. The method of Claim 7, wherein step (c) is performed by finding points on a plot of phase-slowness, and using a non-orthogonal coordinate system to do so.

11. The method of Claim 10, wherein said non-orthogonal coordinate system is defined by a vector pointing along said axis of said borehole, and by a vector pointing along the direction of an image of said borehole.

12. The method of Claim 11, wherein said borehole is inclined at about 45 degrees, such that said borehole and said image of said borehole are generally perpendicular to each other.

13. The method of Claim 7, where in step (b) said recordings comprise waveforms excited by said source; and wherein step (c) comprises the steps of:

- (a) plotting said recorded waveforms as a function of time t and each source-receiver offset s ;
- (b) identifying, on said plot of recorded waveforms, the arrival times of equal phase-points; and
- (c) measuring the slope ds/dt of a curve connecting said arrival times to determine the apparent phase velocity in the s -direction, whereby the inverse (dt/ds) of said slope is the corresponding phase slowness.

14. The method of Claim 13, wherein said waveforms are direct reflected waveforms; and wherein said equal phase points are the peaks of corresponding arrivals.

15. The method of Claim 6, wherein step (c) includes the step of computing

$$V_p(\theta) = V_0 [1 + \delta \sin^2 \theta + \eta \sin^4 \theta]$$

where $V_p(\theta)$ is the sonic P-wave velocity as a function of the angle of propagation θ with respect to the symmetry axis of the medium defined by said lithologic horizons.

16. The method of Claim 6, wherein said raypaths include:

a. a direct borehole-parallel path, with arrival times that are a function of

$$t_1 \quad \text{and} \quad \frac{x}{V_p(\theta)}$$

where t_1 is the arrival time at the first receiver, x is the offset of a given receiver measured from the source and measured parallel to said borehole, and $V_p(\theta)$ is the sonic P-wave velocity as a function of the angle of propagation θ with respect to the symmetry axis of the medium defined by said lithologic horizons.

b. an indirect normal-incidence path, with arrival times that are a function of:

$$t_0 \quad \text{and} \quad \frac{x}{V_{mo}}$$

where t_0 is the time for normal-incidence reflection for the depth from said source to said reflectors comprising geological formation elements and V_{mo} is the moveout velocity; and

c. an indirect path of reflections from said lithologic horizons, with arrival times that are a function of:

$$t_0, \quad \frac{x}{V_{mo}}, \quad \text{and} \quad \sin \theta$$

17. The method of Claim 16, the anisotropy parameter δ and the vertical velocity V_0 are related to said moveout velocity by:

$$V_{mo} = V_0 \sqrt{1 + 2\delta}$$

18. The method of Claim 16, wherein the anisotropy parameter δ and the vertical velocity V_0 are related to said moveout velocity by:

$$V_{mo} = V_o (1 + \delta)$$

19. The method of Claim 16, wherein said plurality of lithologic horizons are dipping; and wherein the anisotropy parameter δ and the vertical velocity V_o are related to said moveout velocity by:

$$V_{mo} = \frac{V_o(\phi)}{\cos \phi} \sqrt{1 + \frac{1}{V_o(\phi)} \frac{d^2 V_o}{d\theta^2}}$$

where ϕ is the dip angle of the lithologic horizon traversed by said sonde in said borehole.

20. Apparatus for measuring seismic polar anisotropy in-situ in a region of the earth that is characterized by geological formation elements that reflect sonic energy and that comprise a plurality of lithologic horizons, comprising:

(a) a housing that is adapted to travel within a borehole having at least one section that has an axis that is deviated from the vertical by a known acute angle and that is located at a known depth, said housing carrying at least one source of acoustic energy into the geological formation elements and a plurality of receivers for receiving acoustic energy from geological formation elements and said source;

(b) a recording system, comprising elements that are located at the wellhead of said borehole and that are in communication with said source and said receivers, for receiving data therefrom; and

(c) means for operating said source and said receivers and for processing data from said recording system in terms of both the direct raypaths from said source to said receivers and the indirect raypaths from said source, through the lithologic horizons that are traversed by said at least one section of said borehole, and to said receivers to obtain measures of at least the seismic polar anisotropy parameters V_o , η , and δ , said indirect ray-paths including reflections from geological formation elements that surround said borehole and at angles different from that of said axis of said at least one section of said borehole, said processing means comprising means for measuring the anisotropic phase slowness over a two-dimensional suite of directions.

21. A method for measuring seismic polar anisotropy in-situ in a region of interest characterized by geological formation elements that reflect sonic energy, comprising the steps of:

(a) using a sonic energy source to input sonic energy into the region of interest, said source being adapted for movement in a borehole that penetrates the region of interest, that is deviated from at least one of the vertical and said formation elements by a known non-zero acute angle;

(b) recording sonic energy from said source and from said geological formation elements by using a plurality of axially spaced apart receivers that are adapted for movement in said borehole; and

(c) interpreting the recorded signal in terms of both direct raypaths and indirect raypaths to measure at least the seismic polar anisotropy parameters V_0 , δ , and η , said indirect raypaths comprising a plurality of reflections from said geological formation elements that surround said borehole and reflections at angles different from that of the axis of said borehole,

wherein the anisotropy parameter δ and the vertical velocity V_0 are related to the moveout velocity V_{mo} by:

$$V_{mo} = V_0 \sqrt{1 + 2\delta},$$

wherein the anisotropy parameters δ and η and the vertical velocity V_0 are related to the P-wave velocity by:

$$V_p(\theta) = V_0 [1 + \delta \sin^2 \theta + \eta \sin^4 \theta],$$

where θ is the angle of propagation with respect to the symmetry axis of the medium defined by said lithologic horizons;

wherein the spacing x of said plurality of receivers located along the axis of the borehole, the P-wave velocity, and the arrival time t_1 at the first receiver are related to the arrival times t at the remaining receivers by:

$$t = t_1 + \frac{x}{V_p(\theta)}, \text{ and}$$

wherein said spacing x of said receivers, said moveout velocity, and the dip moveout time t_0 are related to said arrival times t by:

$$t^2(x) = t_0^2 + \frac{x^2}{V_{mo}^2} + \frac{2t_0 x \sin \theta}{V_{mo}}.$$

22. A high resolution method for measuring seismic polar anisotropy in-situ in a region of interest, comprising the steps of:

(a) inputting sonic energy into the subsurface by using a source located in a borehole that penetrates the region of interest and that is deviated from the vertical by a known non-zero acute angle;

(b) recording sonic energy at a set of receivers located in said borehole; and

5 (c) interpreting the received signal in terms of both direct raypaths and indirect raypaths, wherein said indirect raypaths include reflections from elements within the formations surrounding the borehole and at angles different from that of the axis of the borehole, said indirect raypaths including reflections from lithologic horizons.

10 23. The method of Claim 22, wherein step (c) includes the steps of: measuring the seismic polar anisotropy parameters V_0 , δ , and η ; by computing:

$$V_p(\theta) = V_0 [1 + \delta \sin^2 \theta + \eta \sin^4 \theta]$$

where $V_p(\theta)$ is sonic P-wave velocity as a function of the angle of propagation θ with respect to the symmetry axis of the medium.

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24. The method of Claim 22, wherein said source and receiver are in a single borehole; and said raypaths include:

a. a direct borehole-parallel path, with arrival times given by

$$t = t_1 + \frac{x}{V_p(\theta)}$$

20 where t_1 is the time to the first receiver, and offset x is measured from that receiver; and

b. an indirect normal-incidence path, with arrival times given by

$$t^2(x) = t_0^2 + \frac{x^2}{V_{mo}^2}$$

where t_0 is the time for normal-incidence reflection for the depth from the source to the reflector; and

c. an indirect path of reflections from horizontal interfaces, with arrival times given

25 by:

$$t^2(x) = t_0^2 + \frac{x^2}{V_{mo}^2} + \left(\frac{2t_0x}{V_{mo}}\right) \sin \theta$$

where offset x is the offset of a given receiver, measured from the source, parallel to the borehole, and V_{mo} , the moveout velocity of such reflected arrival, is related to the desired anisotropy parameters by:

$$V_{mo} = V_0 \sqrt{1 + 2\delta}.$$

5 25. The method of Claim 24, wherein $V_0 \sqrt{1 + 2\delta}$ is approximated by $V_0 [1 + \delta]$.

10 26. The method of Claim 22, wherein step (c) comprises the step of measuring the anisotropic phase slowness over a two dimensional suite of directions to characterize the anisotropy of the medium traversed by the rays, said step of measuring the anisotropic phase slowness including the steps of:

- (a) perturbing the position of at least one of said receivers and said source; and
- (b) measuring phase slowness along said axis of said borehole.

15 27. The method of Claim 26, wherein wherein step (c) is performed by finding points on a plot of phase-slowness, and using a non-orthogonal coordinate system defined by a vector pointing along said axis of said borehole, and by a vector pointing along the direction of an image of said borehole.

20 28. The method of Claim 22, where in step (b) said recordings comprise waveforms excited by said source; and wherein step (c) comprises the steps of:

- (a) plotting said recorded waveforms as a function of time t and each source-receiver offset s ;
 - (b) identifying, on said plot of recorded waveforms, the arrival times of equal phase-points; and
 - (c) measuring the slope dt/ds of a curve connecting said arrival times to determine the
- 25 apparent phase velocity in the s -direction, whereby the inverse (ds/dt) of said slope is the corresponding phase slowness.

30 29. The method of Claim 28, wherein said waveforms are direct reflected waveforms; and wherein said equal phase points are the peaks of corresponding arrivals.

30 30. A seismic method, comprising the steps of:

- (a) locating a borehole tool at a non-zero acute angle to the horizon and measuring said acute angle of inclination of said borehole tool, said borehole tool carrying plurality of receivers that are

located along the axis of said borehole and that are spaced apart from one another, said borehole tool carrying a seismic source that is spaced apart from said receivers ;

(b) measuring the spacing of each receiver from said source along said axis;

(c) transmitting seismic energy from a source carried by said borehole tool, and measuring the arrival time at a first receiver that is closest to said source and the arrival times at the remaining receivers;

(d) obtaining a mathematical relationship between the anisotropy parameter δ , vertical velocity and moveout velocity;

(e) obtaining a mathematical relationship between the anisotropy parameters δ and η , said vertical velocity, said angle of inclination of a borehole tool and P-wave velocity;

(f) obtaining a mathematical relationship between said spacing of said receivers along the axis of the borehole, P-wave velocity, said arrival time at a first receiver and said arrival times at said remaining receivers;

(g) obtaining a mathematical relationship between said spacing of said receivers, said moveout velocity, said angle of inclination, dip moveout time, and said arrival times; and

(h) using the measurements of steps (a), (b), (c) and the mathematical relationships of steps (d), (e), (f) and (g) to determine measures of at least said seismic anisotropy parameters δ and η .

31. In seismic exploration of a region of the earth containing at least one of a bedding horizon, a fault, and a layer boundary of a known orientation, wherein a borehole tool is used that carries a plurality of receivers that are located at positions x along the longitudinal axis of the tool and that are spaced apart from one another, and that carries a seismic source that is spaced apart from the receivers, a process comprising the steps of:

(a) locating the borehole tool in a borehole that is inclined to at least one of the orientation of the bedding horizon, the fault and the layer boundary;

(b) recording waveforms from direct raypaths from the source to the receivers and from the indirect raypaths from the source through at least one of a bedding horizon, a fault, and a layer boundary of a known orientation;

(c) obtaining a mathematical relationship between the anisotropy parameters δ and η , the vertical velocity V_0 , the angle of propagation θ with respect to the symmetry axis of the region traversed by the borehole, and the P-wave velocity V_p ;

(d) obtaining a mathematical relationship between the spacing of the receivers along the axis of the borehole, said angle of inclination of the borehole, dip moveout time, and said arrival times; and

(e) using the recorded waveforms of step (b) and the relationships of steps (c) and (d) to obtain the anisotropy parameters V_0 , δ , and η .

32. The seismic method of claim 31, where V_{mo} is a function of V_0 and δ .

33. The seismic method of claim 32, where $V_{mo} = V_0 \sqrt{1 + 2\delta}$.

34. The seismic method of claim 31, where V_p is a function of δ , η , and θ .

35. The seismic method of claim 34, where V_p is a function of V_0 , δ , η , and $\sin^2 \theta$.

36. The seismic method of claim 35, where

$$V_p = V_0 [1 + \delta \sin^2 \theta + \eta \sin^4 \theta].$$

37. The seismic method of claim 31, where said arrival times are a function of x , V_{mo} , θ , and the vertical travel time t_0 .

38. The seismic method of claim 37, where said arrival times are a function of x , V_{mo} , $\sin \theta$, and the vertical travel time t_0 .

39. The seismic method of claim 38, where:

$$t^2 = t_0^2 + \frac{x^2}{V_{mo}^2} + \frac{2t_0 x \sin \theta}{V_{mo}}$$

40. The seismic method of Claim 31, wherein said at least one of a bedding horizon, a fault, and a layer boundary of a known orientation are dipping; and wherein the anisotropy parameter δ and the vertical velocity V_0 are related to said moveout velocity by:

$$V_{mo} = \frac{V_o(\phi)}{\cos \phi} \sqrt{1 + \frac{1}{V_o(\phi)} \frac{d^2 V_o}{d\theta^2}}$$

where ϕ is the dip angle of said at least one of a bedding horizon, a fault, and a layer boundary traversed by said source and said receiver.